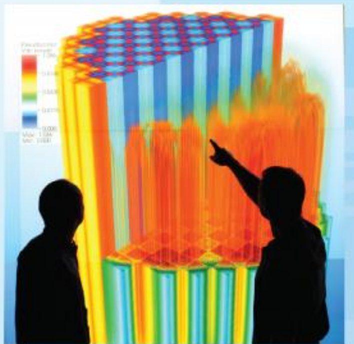
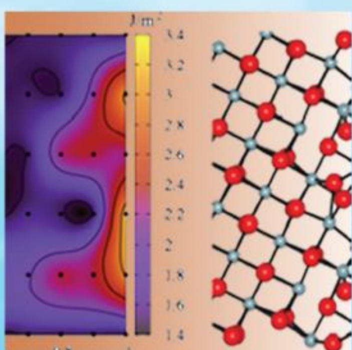
CASL-U-2014-0036-000

Power uprates
and plant life extension

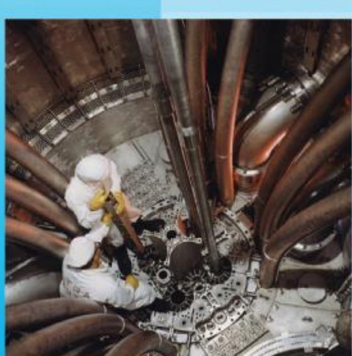


Engineering design
and analysis

Science-enabling
high performance
computing



Fundamental science



Plant operational data

Consortium for Advanced Simulation of LWRs

Industry Test Stand Experience

Stephen Hess, EPRI
Heather Feldman, EPRI
Brenden Mervin, EPRI
Martin Pytel, EPRI
Rose Montgomery, TVA
Bill Bird, TVA
Fausto Franceschini,
Westinghouse Electric Company LLC

Advanced Modeling Applications
28 March 2014

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

REVISION LOG

Revision	Date	Affected Pages	Revision Description
0	3/28/2014	All	Original Report

Document pages that are:

Export Controlled ________None____

IP/Proprietary/NDA Controlled _____None___________________________________

Sensitive Controlled ___None____

Requested Distribution:

To: CASL Senior Leadership Team

Copy: N/A

CONTENTS

ACRONYMS

AMA	Advanced Modeling Applications
CASL	Consortium for Advanced Simulation of Light Water Reactors
CFD	Computational Fluid Dynamics
CP	Challenge Problem
CRUD	Chalk River Unidentified Deposits (industry acronym for all issues related to deposition of impurities on the fuel and reactor internals)
CS	Core Simulator
DNBR	Departure from Nucleate Boiling Ratio
DoE	Department of Energy
EPRI	Electric Power Research Institute
FA	Focus Area
HPC	High Performance Computing
HZP	Hot Zero Power
IFBA	Integral Fuel Burnable Absorber
LPFA	Lower Plenum Flow Anomaly
NPP	Nuclear Power Plant
M&S	Modeling and Simulation
PI	Principal Investigator
PoR	Plan of Record
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
SLT	Senior Leadership Team
TVA	Tennessee Valley Authority
VERA	Virtual Environment for Reactor Applications
WABA	Wet Annular Burnable Absorber
WBN	Watts Bar Nuclear
ZPPT	Zero Power Physics Test

1. INTRODUCTION

The Consortium for Advanced Simulation of Light Water Reactors (CASL) is developing advanced modeling and simulation (M&S) capabilities to provide predictive performance of nuclear reactors with a special focus on several identified Challenge Problems (CPs). These CPs are intended to support development of advanced reactor analysis capabilities that apply high performance computing (HPC) capabilities to analyses of critical issues to commercial nuclear power plants (NPPs). The capabilities being developed by CASL are intended to provide analytical capabilities (methods, models, and computational tools) that can be applied to support NPP power uprates, life extension, and use of higher burnup fuels. A critical element for the success of the CASL M&S hub will be the ability to transfer the technology developed during the research and development effort (both methods and software) to end users (including the industry, regulatory and research communities) and for these end users to be capable of successfully applying these methods and tools to address critical issues related to the long-term efficient and safe operation of commercial NPPs. An important element to enable the achievement of this objective is the development and deployment of industry Test Stands. These Test Stands are intended to serve as a primary mechanism for initial early stage deployment of CASL developed technology to key stakeholders. The Test Stand concept was included in the CASL proposal to the US Department of Energy (DoE) as an important means to achieve early deployment of the M&S technology and to provide a mechanism to obtain stakeholder feedback. Because the CASL technology is in an early stage of development at this time, the initial Test Stand applications are intended to be applied by the CASL core partners that are directly engaged in the operation of commercial NPPs (hereafter referenced as CASL industry partners), i.e. the Electric Power Research Institute (EPRI), Tennessee Valley Authority (TVA) and Westinghouse Electric Corporation (Westinghouse). Since these partners represent a broad spectrum of industry stakeholders (i.e. an industry funded research and development organization, an owner / operator of an integrated fleet of commercial NPPs, and a primary reactor vender involved with the design, construction and technical support for commercial NPPs respectively), these partners provide an ideal initial environment to demonstrate and evaluate the capabilities and tools developed by CASL. It is expected that these organizations can provide constructive criticism and recommendations to CASL and facilitate actions that will enhance the capabilities methods and tools to meet the needs of the broad array of envisioned end users. Additionally, as partners in CASL, these organizations have participated in the CASL research and development and thus have familiarity with the CASL developed methods and tools. Because the CASL developed methods and tools are at a relatively early stage of development, this familiarity enables these organizations to compensate (to some extent) for items that currently are incomplete (e.g. documentation).

Test Stands are intended to provide end users (initially targeted at CASL industry partners but later expanding to other stakeholders engaged in the CASL R&D such as Industry Council members) with an early capability to apply CASL developed tools to problems that are of significance to them. The Test Stand process permits additional demonstrations of CASL developed capabilities on issues that were not directly being addressed as part of the CASL development effort. The Test Stands also are intended to provide direct user feedback to CASL that can be integrated into the CASL work scope and plans.

To support Test Stand selection, in 2012 the CASL Advanced Modeling Applications (AMA) Focus Area (FA) developed a process for evaluation of proposed Test Stand applications. The results of this project were published in the report "Proposed Test Stand Selection Criteria and EPRI, TVA, and Westinghouse Projects" [1] which specified applicable evaluation criteria and a process for selecting the initial Test Stand applications. This report describing the test stand selection criteria also provides guidance for the steps to be taken in selecting Test Stand applications and how they would be executed. In Plan of Record 5 (PoR-5 which occurred April through September 2012), the AMA FA work scope included a milestone L3:AMA.REQ.P5.01 to solicit Test Stand proposals from the CASL Industry Partners and to provide alternatives to the CASL Senior Leadership Team (SLT) for evaluation and ultimate selection of the initial application at each CASL industry partner.

In the selection of a particular Test Stand application, the underlying assumption is that the application would need to represent a "win – win" for both CASL and the organization executing the Test Stand. For CASL, a Test Stand application would be considered a "win" if it applied the Virtual Environment for Reactor Applications (VERA) capabilities to new or different problems that had not been addressed during VERA development and testing conducted by CASL. For the organization executing the Test Stand, an application would be considered a "win" if the application of VERA provided results or insights from use of M&S that were of high relevance to the host organization.

To evaluate the candidate applications proposed by each organization to CASL, a characterization of each of the following attributes was provided to CASL for evaluation by the SLT.

- Relative importance of the issue being investigated to the proposing organization.
- Ability for VERA / CASL tools to support the Test Stand application.
- Readiness of CASL capability / amount of additional development required to support the application.
- CASL funding requirements.
- Ability to provide useful information and feedback to CASL to support further VERA development.

These criteria thus represent a diverse set of attributes against which the applications proposed by each partner institution could be evaluated. It should be noted that these criteria and the evaluation of each proposed application against them were intended to serve as guides in the selection process. In each instance a number of conversations between the CASL and the industry partner were conducted to select the particular application for that partner's Test Stand that was believed to provide the greatest combined "value" to both CASL and the industry partner. From these discussions a final decision was made on the application for each Test Stand host organization. It should be noted that these selections were documented via correspondence between each CASL industry partner and CASL in the form of a Test Stand proposal letter from the partner and an acceptance letter from CASL. (Note that the final versions of this documentation were the result of several rounds of discussions between CASL and each Test Stand host organization.)

In response to the initial Test Stand solicitation, each CASL industry partner provided a selection of candidate applications for CASL to evaluate. In this response Westinghouse proposed 4 potential candidate applications; EPRI also proposed 4 and TVA proposed 7. These proposed projects also are described in reference [1]. These proposals were reviewed and projects were selected from each CASL industry partner that best met the criteria and was agreed to provide significant "value" and achieve the desired "win – win" outcome. As a result the following applications were chosen:

- Westinghouse – analysis of initial core load for the **AP1000**® reactor using the VERA-CS code contained in VERA.
- EPRI – pellet to clad interaction (PCI) analysis using the Peregrine fuel performance code contained in VERA with comparison to results from the EPRI Falcon code.
- TVA – evaluation of the Lower Plenum Flow Anomaly (LPFA) phenomenon using the Hydra-TH code contained in VERA.

Since the Test Stands are being implemented in stages (with the Westinghouse Test Stand first, followed by EPRI and finally TVA) this report provides a discussion of the experiences obtained *to date* from each Test Stand application. At this time the work on the initial Westinghouse Test Stand is essentially complete and has been reported to CASL in Reference [2]. Work on the EPRI Test Stand has only recently begun; however some *initial* observations and recommendations can be made. Work on the TVA Test Stand is currently in the planning phase. The next three sections of this report describe the experience (to date) of each partner's Test Stand respectively. The final section presents a brief integrated summary of the Test Stand experiences of the CASL industry partners and a set of recommendations for enhancements resulting from these experiences.

It should be noted that the intent of this report is *not* to provide detailed descriptions of technical results achieved (and which, at this time are only available for the Westinghouse Test Stand application); rather the focus of this report is to describe the experiences each partner has had with their Test Stand and to provide any relevant recommendations to CASL that result from those experiences. For detailed technical results associated with the Westinghouse Test Stand the reader is referred to reference [2]. (Note – for convenience this report can be accessed at the CASL website via the following link http://www.casl.gov/docs/CASL-U-2014-0012-001.pdf)

Since the experiences described in the following sections are indicative of the separate experiences of the three CASL industry partners, it was decided that each partner would provide descriptions of their particular experiences. As a result, each partner wrote their particular section independently. Thus, each section provides that partner's perspective on their Test Stand experience. In the compilation of this summary report, each section was incorporated essentially as provided by each partner to permit each partner's perspective to stand on its own. However to provide the reader with some additional perspective, the relevant characteristics of each Test Stand are summarized in Table 1-1 below. This summary provides a consolidated listing of the key characteristics and approaches taken for each of the Test Stand applications described in the following sections.

CASL Partner	Application	Tool / Characteristics	Approach	Status
Westinghouse	ZPPT modeling of **AP1000** PWR first core design	Application of VERA-CS. Status of VERA-CS at time of Test Stand deployment included an initial demonstration of VERA-CS but did not include all elements necessary for conduct of analyses. At the time of Test Stand deployment VERA-CS capabilities needed for execution were still undergoing active development and some issues were fixed during the execution.	Principal Investigator (PI) is experienced in core design, method validation and use of advanced reactor analysis tools. PI has been previously engaged with CASL AMA FA but had limited direct experience with VERA-CS when the analysis was started.	Complete
EPRI	Fuel performance analysis using Peregrine	Application of Peregrine fuel performance analysis module. At time of Test Stand deployment Peregrine capabilities needed for execution were still undergoing active development.	PI is recent PhD graduate with minimal prior interaction with CASL. EPRI mentor has extensive experience in fuel performance modeling (served as EPRI lead for the development of the Falcon code) and has had previous engagement with CASL AMA; however he has had minimal interaction with the Peregrine development team.	In Progress
TVA	Evaluation of Lower Plenum Flow Anomaly (LPFA) using Hydra-TH	Application of Hydra-TH CFD methodology / code. At time of Test Stand deployment Hydra-TH capabilities needed for execution are still undergoing active development.	Test Stand in planning with specific TVA resources to be used still being identified.	Planning

Table 1-1: Summary of Characteristics for Initial CASL Test Stands

2. WESTINGHOUSE TEST STAND

The Westinghouse Test Stand application used the Core Simulator (CS) capabilities of VERA to conduct Zero Power Physics Test (ZPPT) simulations for the **AP1000** pressurized water reactor (PWR) core design. This activity was conducted during PoR-8 (October 2013 – March 2014) by Westinghouse as part of CASL AMA milestone AMA.VDT.P8.01. This milestone was completed on 31 January 2014 with results documented in CASL report "Westinghouse VERA Test Stand: Zero Power Physics Test Simulations for the **AP1000** PWR" [2]. The Westinghouse Test Stand report provides details of the following activities and results:

- Westinghouse Test Stand Experience
- Description of VERA Build
- Description of **AP1000** PWR First Core Design
- M&S Approaches Used
  - VERA-CS
  - KENO-VI
- Results Obtained
  - 2D Lattice
  - 2D Multi-Lattice
  - 2D Core
  - 3D Single Assembly
  - 3D Multi-Assembly
  - Zero Power Physics Tests
- Computational Requirements
- VERA Usability
- KENO Monte-Carlo models
- Reflector sensitivity studies

This work represents the first completed application of CASL developed technology in a Test Stand environment. Since the intent of the present report is to provide the experiences and lessons derived from the initial Test Stand deployments for each of the CASL industry partners, in this report we only present a summary of key insights obtained by the completed work at Westinghouse. For detailed technical results from this work the reader is referred to the milestone report for CASL AMA milestone AMA.VDT.P8.01 [2]. In this section of the Test Stand experience report the majority of information relevant to our objectives is contained in the following sections of the Westinghouse Test Stand milestone report:

- Section 2 – The Westinghouse Test Stand Experience
- Section 8 – Usability of VERA-CS

Thus, in this section of the Test Stand experience report we provide a summary of these experiences (mostly extracted from [2]).

The technical analysis for the Westinghouse VERA Test Stand application began at the end of June 2013, with the release of VERA built on the Westinghouse cluster-based computational system. Westinghouse selected a challenging application for its VERA Test Stand: the **AP1000** PWR first core. The **AP1000** reactor is an advanced reactor design with enhanced passive safety and improved operational performance that builds on decades of Westinghouse's experience with PWR design. The first eight units are currently being built in China and the U.S., and represent the first Generation III+ reactor to receive Design Certification from the U.S. Nuclear Regulatory Commission. The **AP1000** PWR first core is a considerable advancement compared to past first cores of commercial PWRs; it features a novel uranium zoning scheme, which allows more efficient and cost-effective fuel usage, a combination of burnable absorbers for power distribution control, and the MSHIM™ operation and control strategy. MSHIM is an advanced operational strategy that provides robust core reactivity and axial power distribution control with minimal changes to the soluble boron concentration in the reactor coolant, during both normal operation and power maneuvering scenarios. This strategy takes advantage of an increased presence of control rod clusters in the reactor core during at-power operation, which entails additional challenges on simulation. These advanced features of the **AP1000** PWR, and the imminent deployment in the units under construction, made for a relevant and engaging application of CASL technology since VERA was employed to provide information to support Westinghouse's startup predictions, to investigate the potential improvements in the characterization of advanced cores fostered by VERA-CS compared to traditional modeling approaches and to generate a set of numerical benchmarks of rare geometrical complexity as well as operational relevance. The results of these simulations reinforced the confidence in Westinghouse's predictions obtained with their in-house core physics tools and licensed methods, plus indicate areas of potential improvements to guide future methods development at Westinghouse. For these reasons this Test Stand, with the results already obtained and those to come in the future now that the codes have been deployed on the Westinghouse cluster, is viewed by Westinghouse as possessing extremely high value.

The extensive set of simulations performed throughout the conduct of the Westinghouse Test Stand with the detailed results are presented in reference [2], together with detailed feedback on VERA's usability, computational performance, modeling approach, results validation, build process and recommendations for improvement. This outcome represents a compelling demonstration of the potential long-term value that VERA-CS has as an advanced M&S framework and will provide to industry.

In the results obtained from the Westinghouse Test Stand application, VERA accurately reproduced Monte-Carlo numerical benchmarks from the KENO code for the hot zero power (HZP) **AP1000** PWR core, with a level of consistency in the agreement beyond that of the typical commercial core simulators. While more extensive comparisons are required before making definitive conclusions, this performance is auspicious for the adoption of VERA by the industry to complement and augment their existing suite of production tools and licensed methods. The successful completion of the development of VERA-CS will enable obtaining high-fidelity predictions for a range of commercial PWRs and operating conditions that would be used by the nuclear industry for a variety of applications, such as anticipating or mitigating operational issues, troubleshooting mis-predictions of plant measurements, benchmarking new methods, and corroborating the design of advanced

MSHIM is a trademark of Westinghouse Electric Company LLC in the United States and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited.

cores. The scope of this Test Stand and the results obtained represent an example of these potential applications.

Westinghouse reported that the benefits of their Test Stand went beyond the technical analyses performed. A summary of these benefits is provided below. Conversely, there were some challenges in the preparation and execution of the Test Stand; however these were resolved due to the efforts expended by both CASL and Westinghouse to resolve them.

As a result of the Test Stand experience at Westinghouse, the performance of VERA for the **AP1000** core simulations, and the physics methods underpinning such performance, has generated significant interest within Westinghouse. This outcome stimulated a healthy discussion between Westinghouse and the CASL method developers which is perceived as being mutually beneficial with expectations that these interactions will continue in the future. The scale of the simulations performed for this work and the degree of confidence in their accuracy supported by the comparisons with Monte-Carlo codes such as KENO are an important outcome of the Test Stand.

The installation of VERA on Westinghouse's computer cluster was performed jointly by CASL and Westinghouse staff. As a result, a procedure for building VERA was created as part of the Test Stand activities and documented in the "VERA Installation Guide". As discussed in the next section (EPRI Test Stand) this report provides significant benefits for future VERA deployments. The Westinghouse VERA build has been ported to a different, more powerful, computer system since its original installation, and it has been successfully updated to include VERA developments that have been crucial to the Test Stand execution. A section of reference [2] provides technical details associated with the VERA build on the Westinghouse computer platform.

VERA is computationally demanding compared to typical industrial core simulators, and in order to execute the Test Stand simulations Westinghouse has purchased a dedicated VERA computer cluster consisting of 576 compute cores with a 32 core login node. This purchase represents a significant enhancement beyond the typical computational resources used by the industry to perform reactor physics analyses. This system consists of an industrial class HPC with the following characteristics:

- Compute – Intel® Xeon® X5670 (12M Cache, 2.93 GHz, 6 Cores)
- Size – 576 Compute Cores + 32 Cores on Interactive Login Node
- Mass Storage – Up to 1 PB
- Memory – 8 GB RAM / Compute Core (4.6 TB) + 1 TB on Interactive Login Node
- Interconnect – QDR Infiniband

This system is also indicative of industry class computing platforms that could be made available for use of VERA within the nuclear industry, and hence of the computational resources that VERA needs to meet for its deployment at industry's sites. One observation reinforced by Westinghouse as a result of this Test Stand experience is that resorting to the use of leadership class HPC platforms (e.g. Titan) to run VERA does not represent a sustainable path forward if VERA is to receive widespread adoption by the industry. This awareness was confirmed by the Test Stand execution. As one example of this conclusion, the HZP **AP1000** PWR simulations are already at the limit of the current computational resources available on the Westinghouse VERA dedicated cluster; thus the computational burden required for VERA execution is one element that needs to be mitigated before widespread adoption of VERA by industry could realistically be expected. The current computational burden of VERA makes core cycle depletion calculations impossible or impractical. CASL has not yet focused efforts on optimizing the computational performance of VERA; thus it is reasonable to anticipate that such efforts, together with the projected advancement in computational capabilities of industry class computing platforms, will address these concerns.

While at the limit of the computational resources available, it was possible to perform all the ZPPT VERA calculations on the Westinghouse VERA computational cluster. The resulting VERA predictions reported in reference [2] are in excellent agreement with counterpart Monte Carlo calculations, requiring ~50 times the number of core-hours employed by VERA.

In addition to evaluating the performance of VERA during the Test Stand, a second critical element of VERA that was assessed was its usability. During the Test Stand application, VERA-CS models were set up through VERAIN, the VERA common input [3]. The format of this input was found to be intuitive and comprehensive and, after a short learning period, Westinghouse engineers were able to set up a complete 3D core model of the **AP1000** PWR first core in a compact ASCII file. A depiction of the **AP1000** PWR first core KENO model together with a sample portion of the VERA input is given in Figure 2-1. An example of the simulations performed for the Test Stand is given in Figure 2-2.

While there are some limitations in the current VERAIN modeling capabilities, there appear to be no inherent barriers preventing future extension of the current features. The convenience of the common input is seen as an important point of merit for VERA.

As a spinoff of the Test Stand simulations, calculations using the Monte-Carlo capability under development in CASL with the SHIFT code have also been performed. The intent was to obtain a 3D core low-uncertainty Monte-Carlo solution for power distribution comparisons**.** While not intended to be the workhorse for cycle depletion calculations, SHIFT adds the convenience of using the VERA common input to massively parallel capabilities which allow obtaining power distribution with very low statistical uncertainty across large geometries, up to 3D core. An example of the SHIFT results obtained for the **AP1000** PWR core is given in Figure 2-3. This simulation is a 5-hr computer run with 10^{12} particle histories performed on ~230,000 cores at the ORNL “Titan” Leadership Computing Facility, as part of a 60 million core hour allocation that a joint ORNL and Westinghouse team was awarded during this project (Ref. [4]).

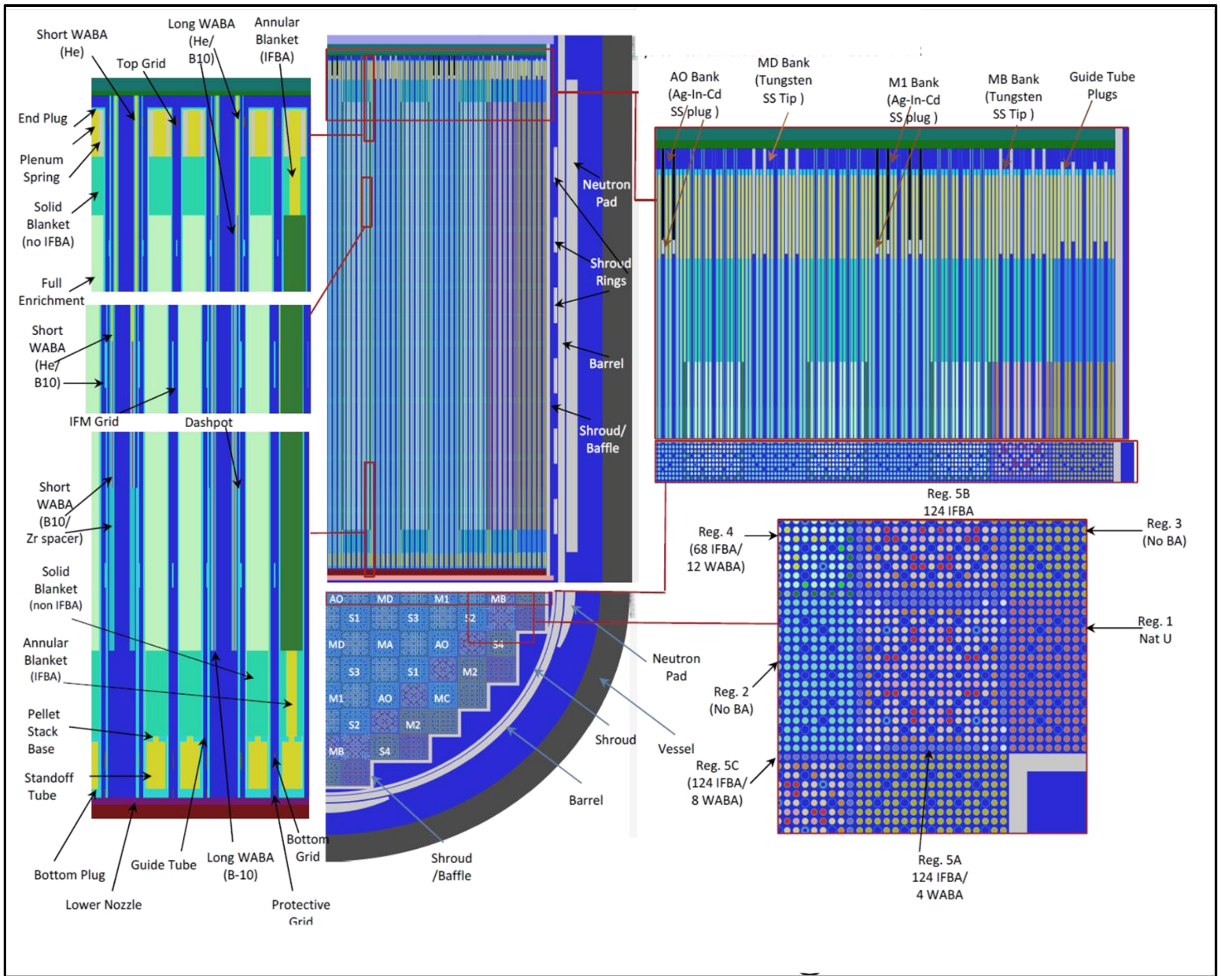


Figure 2-1: AP1000 PWR 3D core KENO model with excerpt of VERA input cards.

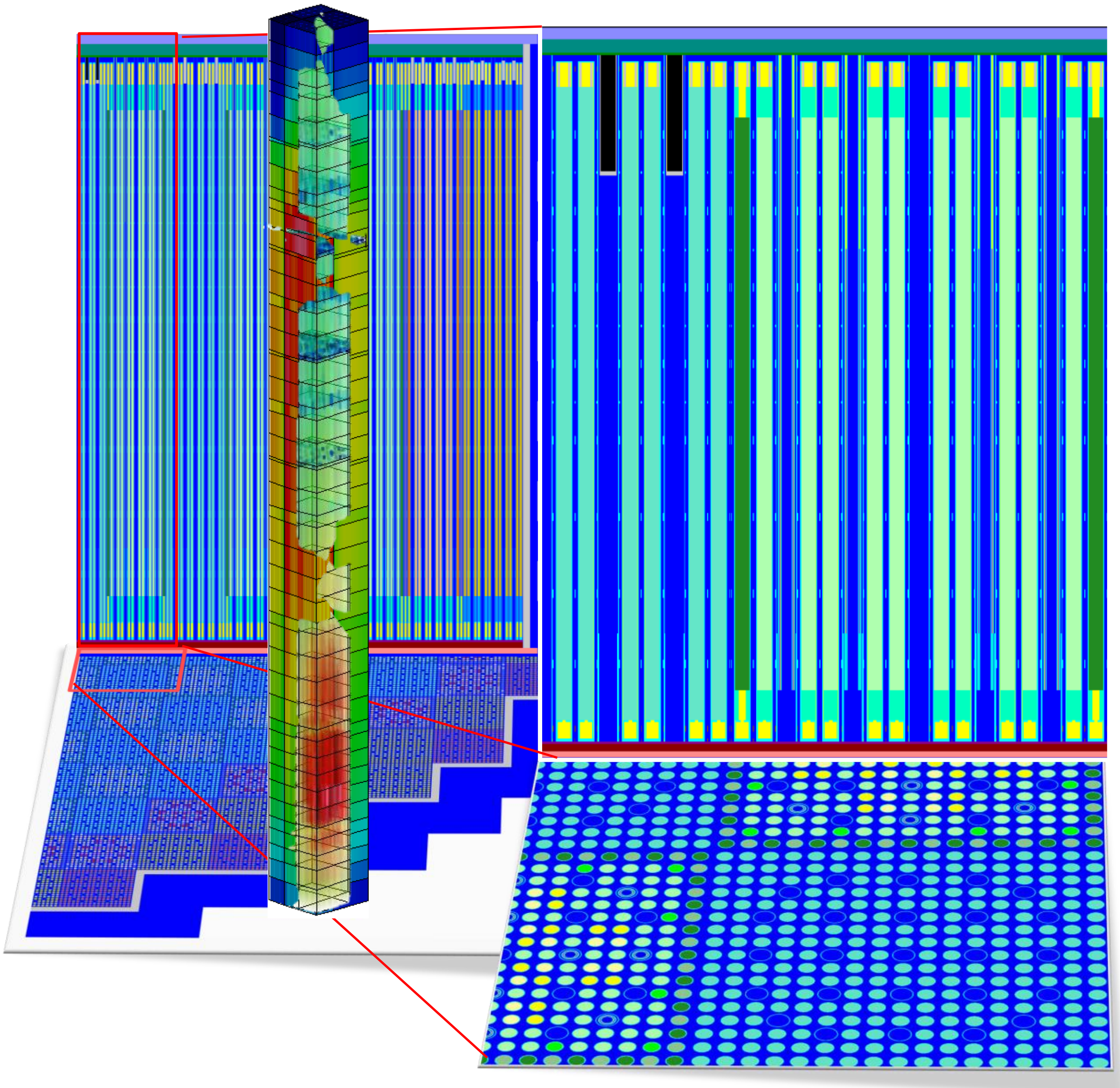


Figure 2-2: Power distribution and % delta power VERA-CS vs. Monte-Carlo KENO for 3D multi-assembly with partial insertion of the Axial Offset Control Bank in the center assembly. (One of the simulations executed as part of the Westinghouse Test Stand.)

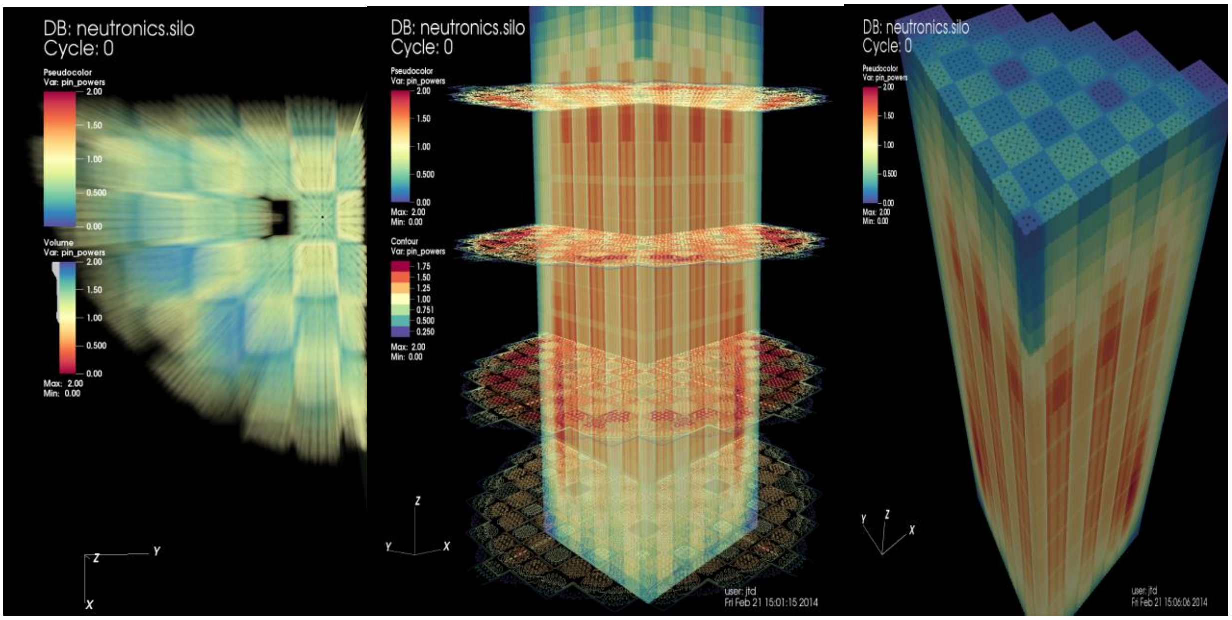


Figure 2-3: Power distribution with the SHIFT Monte-Carlo code for a 3D core simulation with multiple control bank insertion to emulate the **AP1000** PWR MSHIM operation.

Another favorable feature of VERA is the "one-step" simulation approach which favors compactness and flexibility in the input structure. One example of this flexibility is the input structure for the inserts (i.e., WABA, control rods), which are set-up independently from the fuel assembly where they are inserted. In addition to the Test Stand application to the **AP1000** PWR core Westinghouse also has successfully modeled another commercial PWR (a 2-loop PWR core) using VERA. For this application the resulting modeling effort was modest, amounting to a few hours, and the comparison with the plant measured HZP start-up critical boron was outstanding. In general it was concluded that the average core designer should find simulation set-up for VERA to be a relatively easy effort, especially if provided with representative sample input decks. This is a significant accomplishment that demonstrates VERA's accuracy as well as the convenience of the common input as this plant is of a significantly different design than either the **AP1000** PWR core design used in this Test Stand or the Watts Bar plant which is serving as the reference plant for CASL development and validation.

The main limitations in the current VERA modeling capabilities noted as part of the Westinghouse Test Stand are the following:

- No automatic accounting for the thermal expansion of fuel and structures from cold to hot conditions.
- Limitation of the reflector model to a "jagged" (e.g. baffle-like) structure surrounded by water.
- No provision for direct assignment of material number densities to a given cell.
- Other limitations in VERA-CS modeling capabilities that could arise as fuel geometries are extended to arrays other than typical square-pitch fuel assemblies were not encountered during this Test Stand application; however the potential for such issues should be kept in mind when other industrial applications are considered.

We note that since a principle objective of the CASL Test Stand deployments is to obtain such user feedback, the identification of these limitations provides useful information for CASL to incorporate into future versions of VERA; thus enhancing the utility of the tool to eventual end users.

In terms of execution, VERA-CS simulations are run via a short shell script launched from the terminal window. This is similar to other core simulators. Westinghouse did not find this process to be particularly challenging nor are there any significant recommended improvements.

VERA-CS execution was found to be robust and stable. There were no instances where a calculation failed to converge or converged to an unphysical result. This is a remarkable behavior for a code system at this stage of development indicating the quality of the physics methods adopted and of the software implementation. There were instances of failed executions due to lack of enough memory to perform the calculation being attempted. Additionally, the determination of the amount of required memory currently is a "trial and error" process.

Another area identified for improvement is documentation. At this time the user manuals supporting VERA-CS are inadequate. It is recommended that concerted efforts be made to systematically document the options available and the methods employed for the various components associated with VERA-CS, especially considering the needs and potential support requests that could be anticipated when VERA-CS is deployed to the broader community of users.

In summary, at the current state of development, the Westinghouse Test Stand determined that VERA-CS was convenient to use by the average engineer after an initial, reasonably short, learning period with support provided from CASL personnel. Listed in decreasing priority (as presented in reference [2]) improvements in terms of features, documentation, build process, and I/O could be made but due to ongoing developments with constrained resources, they should not be considered urgent. It was recommended by the Westinghouse Test Stand participants that priority should be given to implementing treatment of thermal expansion and enhancement of the reflector modeling capabilities.

As a final remark on VERA's usability from the perspective of the Westinghouse Test Stand participants, the two most significant enhancements needed to permit use by industry stakeholders are (1) obtaining substantial reductions in the required computational resources (memory, compute cores and wall-time) and (2) implementing capabilities for cycle depletion with coupling.

3. EPRI TEST STAND

The EPRI Test Stand application will test the fuel performance components of the VERA software, specifically the Peregrine fuel performance code [5] and its ability to perform pellet-cladding interaction (PCI) analyses. This work is currently being conducted by the Electric Power Research Institute (EPRI). At present, all of the preliminary work such as training EPRI personnel and installing the VERA software has been completed, and execution of the Test Stand is now underway. EPRI's overall experience with the Test Stand to date has included both positive and negative aspects. Positive experiences include the setup of VERA and Peregrine training. The primary negative experience is associated with the current limitations in the Peregrine code. During the training session, the capabilities currently available in VERA (Peregrine) were discussed. Based on that discussion, EPRI determined that many of the tasks initially proposed for the Test Stand cannot be performed within the scheduled time frame that was originally proposed to and accepted by CASL. EPRI believes that the review of the Test Stand scope and subsequent discussions between EPRI and CASL should have identified the limitations that would be caused by the Peregrine development schedule. As a result of this occurrence, EPRI has revised the Test Stand scope and this revision is currently under review by CASL.

This document describes EPRI's experience with each of the following Test Stand activities:

- Test Stand Setup and VERA Installation
- Training
- Status and Capabilities

Each of these sections provides a description of the respective Test Stand activities that were accomplished, an assessment of these activities and recommendations to CASL for enhancements.

3.1 TEST STAND SETUP AND VERA INSTALLATION

The initial installation of VERA (VERA 3.3 DEV) on EPRI's industry class high-performance computer, Phoebe, was completed on October 18, 2013 by EPRI staff with the assistance of CASL support personnel. Phoebe consists of an industrial class HPC Hewlett-Packard ProLiant SL6500 Scalable System with the following characteristics:

- Compute – Intel® Xeon® Processors consisting of
  - one head node with 4 GB/core and 1.2 TB Hard Disk Drive
  - 31 compute nodes with 4 GB/core and 300 GB Hard Disk Drive
  - one compute nodes with 16 GB/core and 300 GB Hard Disk Drive
- Size – 496 Compute Cores
- Mass Storage – 100 TB
- Memory – 2 TB
- Interconnect – QDR Infiniband
- Speed – 8 Theoretical Teraflops

To support a broad range of EPRI developed software applications Phoebe provides dual boot capability for both the Linux and Windows operating systems. CASL has prepared a variety of tools to aid in executing the installation and setup tasks, which can be quite cumbersome without proper knowledge of all of the underlying components and the Linux operating system. Performing some of the general bookkeeping tasks such as accessing the code repositories and installing VERA was greatly simplified by the VERA Installation Guide provided by CASL. The automation provided by CASL for performing these tasks was also quite helpful in expediting the overall build process. We note that ease of installation and testing for VERA demonstrates one of the benefits obtained from the Test Stands. As discussed in the previous section on the Westinghouse Test Stand, one of the benefits of that deployment was the development of a useful installation guide. This outcome from that Test Stand contributed significantly to the ease of installation of VERA on Phoebe experienced by EPRI.

It should be noted that use of HPC architectures is new to EPRI as Phoebe came online late in 2013. Thus, this support was extremely helpful to EPRI and would also be considered important going forward as the technology is eventually made available to the broader community of end users. The Phoebe high-performance computing cluster at EPRI represents significant value to the execution of the EPRI Test Stand which is considered to be a critical component of EPRI's strategy to engage in research and development that could benefit from HPC capabilities. Phoebe provides EPRI with an industry class HPC capability with which EPRI can test the VERA software. For the CASL Test Stand it also provides an internal location in which multiple users could utilize the same verified installation of VERA. Noting that VERA is primarily developed for high-performance computing environments ranging from industry class to leadership HPC architectures, Phoebe enables EPRI to test the VERA software within its targeted environment.

As indicated previously, VERA installation onto Phoebe was a relatively straightforward and transparent activity. One special deviation from a standard VERA installation was necessary to support the EPRI Test Stand installation. This activity required the installation of a stand-alone version of Peregrine, which is the VERA component that is the focus of the EPRI Test Stand. This activity was not documented in the VERA installation guide, but was enabled by CASL support staff; thus it did not impact VERA installation on Phoebe. <u>As a result of this experience, it is recommended to include specifics for this (and similar stand-alone) installations in the VERA Installation Guide as an appendix to enable it as a standard capability until it becomes fully integrated into VERA.</u>

EPRI views the Test Stand as an "alpha" application of VERA, thus it was expected that complications would arise during the set-up process. When these issues arose, EPRI personnel contacted CASL support staff and a support ticket was created where EPRI staff could monitor the conversations between CASL support staff as they worked on resolving the issues. This was a significant benefit to the EPRI personnel who submitted the issues as they were able to verify that progress was being made and to get instantaneous feedback and support. EPRI's overall experience with the process to resolve the issues that arose via interfacing with CASL support staff was satisfying as the CASL staff was expedient about addressing the installation issues and aiding in the troubleshooting process throughout the course of the installation. The only significant challenge observed during this process (beyond what would typically be expected) involved needing to wait for changes and information from the Peregrine development team to propagate back to EPRI. This process took more time than EPRI expected. <u>EPRI believes this process could be improved for support of future VERA deployments and recommends that CASL review the internal processes and</u>

protocols when individual code developers (e.g. Peregrine, MAMBA, etc.) are needed to provide end user support.

After initial installation of VERA on Phoebe, several issues arose as EPRI personnel began attempting to run and test the Peregrine portions of the VERA software. The first issue encountered was an observation that the available user documentation corresponded to a newer version of Peregrine than what was provided for installation on EPRI's computational cluster, with no documentation being provided for the version of Peregrine EPRI installed and that would be used during the Test Stand. Therefore an updated installation of VERA was necessary in order to have a version of Peregrine that was consistent with the training and reference materials provided. EPRI recommends that CASL review its configuration control and release protocols to ensure that the correct documentation (including installation, testing and user manuals as appropriate) is provided for each capability contained within VERA.

The last task which required completion prior to the execution of the Test Stand was to verify the new installation. To perform this verification, a suite of regression and validation tests needed to be run using the newly installed software. During this validation it was discovered that the version of one of the required third-party libraries, imposed by the MOOSE system (developed at Idaho National Laboratory (INL) [6]), which is the framework on which Peregrine is built, was newer than what is required for testing the VERA software. Installing a newer version of the third-party library was performed without issue, and the tests were run successfully. The expected results were then obtained and passed along to the Peregrine development team for evaluation and verification of proper installation of Peregrine on Phoebe. The reason these test results needed to be sent to the Peregrine development team was because one of the Peregrine tests failed during this verification process. EPRI believes that the cause of this issue is similar to the others encountered and this reemphasizes the EPRI recommendation for CASL to review the configuration control and internal CASL communications processes and protocols.

3.2 TRAINING

To support the EPRI Test Stand deployment, a Peregrine training workshop was conducted on February 6th and 7th of 2014 at the EPRI offices in Charlotte, NC. The Peregrine training sessions were very enlightening, especially because the personnel who administered the training (which included the Peregrine development team) were able to make comparisons between Peregrine and EPRI's fuel performance code, Falcon. Furthermore the quality of the presentations and their delivery were excellent as well as the usage of the limited time available during the training sessions [7]. EPRI staff gained considerable knowledge about the current capabilities of Peregrine, the ongoing development activities, and the necessary information needed to run Peregrine. This enabled EPRI to re-assess the Test Stand scope.

The Peregrine training workshop was a day and a half in duration and primarily covered topics specific to the Peregrine application. The training included a good explanation of background and overview material associated with light water reactor (LWR) fuel performance analysis, and the methods and input procedures for using Peregrine for one example case. Peregrine is itself a fuel performance code specific to light water reactor applications; it is part of a broader more generic fuel performance modeling capability in the INL BISON code that is built upon the MOOSE computational framework [6]. Thus, such a short duration training session was simply not enough time to perform all of the necessary training. The CASL staff who provided the training made efficient use of their time in training EPRI staff on most aspects of Peregrine and its underlying infrastructure. CASL provided help to EPRI staff in resolving issues encountered with Peregrine. Additional training sessions are being discussed for EPRI personnel. From the perspective of experience gained from the EPRI Test Stand, when the VERA suite is made available to the broader universe of industry stakeholders (i.e. nuclear plant owner / operators, fuel vendors, or regulatory agencies) a much more comprehensive training program will be needed to permit users who have not been involved with the VERA development effort to effectively utilize this software. EPRI recommends that CASL include development of training modules for each of the capabilities included in VERA (core simulator, Peregrine, MAMBA, etc.) as a specific activity that can be provided to end users when VERA is deployed.

3.3 STATUS & CAPABILITIES

Once VERA installation and testing were complete and EPRI personnel responsible for the Test Stand execution were trained on Peregrine, actual execution of the Test Stand commenced in early February. The activity selected for this Test Stand deployment was analysis of the Pellet to Cladding Interaction (PCI) of Watts Bar 1 fuel rods during the startup of a 2nd fuel cycle. This initial simulation topic will use VERA to screen the Watts Bar core for rods that are susceptible to PCI and perform a PCI margin assessment with the intent to use the criteria presented in EPRI's Fuel Reliability Guidelines on PCI described in EPRI report 1015453 [8] for comparisons.

At the time this report is being written, EPRI is at the early stages of conducting the Test Stand assessments. However, a number of observations from the experience to date are relevant and recommendations resulting from them are viewed as having importance and value to CASL.

As mentioned previously, the Peregrine code has limited external user support at this time; thus it is extremely difficult for an end user to perform analyses that go beyond the methods that were illustrated in the example cases presented during the training. EPRI views the Test Stand as an "alpha" application of VERA and EPRI expected the available Peregrine documentation to be comparable to what industry would expect in an alpha deployment of a software product. The currently available documentation for Peregrine is not at the level industry would expect to accompany an "alpha" deployment. EPRI recommends that CASL devote attention to developing acceptable levels of documentation for Peregrine and all VERA codes to support these envisioned near-term deployments. This level of documentation should, at a minimum, provide information on capabilities and use as specified in the VERA Requirements Document (VRD) [9]. If specific information is not developed or available at the time of the deployment this should be indicated so that appropriate actions by CASL or the organization sponsoring the Test Stand can be developed and implemented.

One proposed task for this Test Stand was to perform PCI analysis and margin assessment using data obtained from the Tennessee Valley Authority for the Watts Bar Unit 1 reactor. The current industry standard method of analysis uses a 22.5° R-θ slice model (shown in

Figure 3-1 below) and represents the procedure previously developed by EPRI for performing PCI analysis using the Falcon fuel performance code [8, 10].

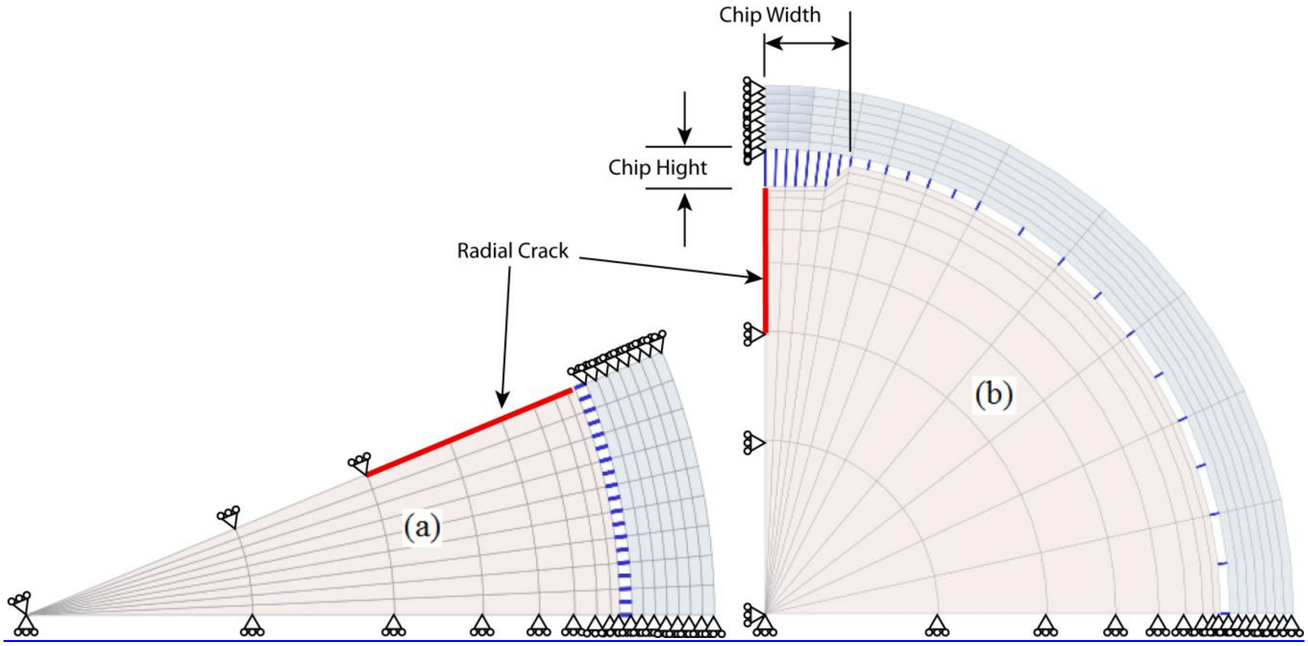


Figure 3-1: Falcon (a) Radial Crack R-Theta Model and (b) 90 degree MPS R-Theta Model [10].

During discussion of the proposed EPRI Test Stand application it was identified that some of the Peregrine capabilities needed for this application were still under development. While extensive testing of the 2D R-Z modeling capabilities has been completed, EPRI was informed that 2-D R-θ testing was in progress with results expected within a few weeks. As a result of the CASL response memo sent in October of 2013 the decision was made to proceed with the proposed Test Stand application as it was assumed by EPRI that the capabilities would be ready in sufficient time to support the application. Although some R-θ modeling capability currently is included in Peregrine, it is not at a level sufficient to support complete industry standard PCI analyses at this time. Currently Peregrine models a 90° slice model as shown in Figure 3-2. The primary issue associated with this model is that the method for imposing boundary conditions to fix displacements in the θ-direction for locations other then 0°, 90°, 180°, and 270°, has not been developed in manner which would support straightforward modeling for a single explicit crack at other angles.

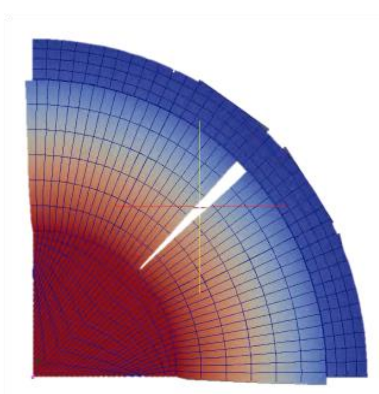


Figure 3-2: Peregrine explicit crack model [7].

As a result of this situation, EPRI has developed a revised Test Stand work scope that accurately reflects the current (and near-term) capabilities of Peregrine which can be accomplished within the originally proposed timeframe for the Test Stand. This revised proposal currently is under review by CASL. To preclude revising of the technical scope for future Test Stands, EPRI recommends that CASL thoroughly review its configuration control and release protocols to ensure the technical capabilities in VERA are sufficient to support the Test Stand application being proposed. As an enhancement to better support a general VERA deployment to the broad end user community, EPRI also recommends that CASL develop a description of capabilities included in the particular VERA release that provides sufficient detail to support an end user determination to what extent VERA can support the analyses being planned. For a Test Stand deployment particular attention should be placed on providing this information for the specific VERA components that will be used in the conduct of the Test Stand analyses.

3.4 SUMMARY

One of the key objectives of Test Stands is to get early involvement of end users to identify the areas for improvement to the deployment process and capabilities of VERA. Up to this point the Test Stand experience at EPRI has resulted in both positive and negative user experiences. The primary positive experiences to date are the excellent support provided by CASL staff to install and test VERA on EPRI's industry class computing cluster, Phoebe, and the quality and value of the Peregrine training session provided by CASL. On the other hand, while the Peregrine-specific fuel modeling capabilities in the R-Z geometry are coming together well (the contact and friction models in the MOOSE framework remain under active development), the actual capabilities of Peregrine to perform the R-θ component of PCI analyses have been disappointing to the EPRI fuel performance personnel involved with the Test Stand application. It is however recognized that this capability is under active development within CASL and that EPRI will begin the process of exercising this function as their experience with the code increases.

As a result of the EPRI Test Stand experience to date, two significant recommendations (specific recommendations are underlined in the previous sections) can be made to CASL as areas for improvement:

(1) Test Stand Deployment Review: The issues encountered by EPRI in the disconnect between the capabilities needed to execute the planned Test Stand application and the capabilities currently supported by Peregrine were due to insufficient communication between CASL and EPRI during discussions of the planned work scope. EPRI recommends that CASL evaluate its configuration control and release protocols to ensure the technical capabilities in VERA are sufficient to support future Test Stand applications that may be proposed. Additionally, to support a general VERA deployment to the broader end user community, EPRI also recommends that CASL develop a description of capabilities included in the particular VERA release that provides sufficient detail to support an end user determination to what extent VERA can support the analyses being planned.

(2) Peregrine Documentation: EPRI experience indicated that this documentation is insufficient even at the level of an alpha release. EPRI recommends that CASL devote significant attention to developing acceptable levels of documentation for Peregrine to support envisioned near-term deployments. Also, because this is an issue generic to all of the capabilities contained within VERA and will be needed to support a general VERA deployment to the broader end user community, EPRI recommends that CASL review the

current state of documentation for all of the VERA capabilities and implement appropriate actions to develop a consistent set of documentation for each application.

Since these issues are directly applicable and necessary to support a general deployment of VERA to the broad community of external stakeholders (i.e. nuclear power plant owner / operators, fuel vendors and regulatory agencies) targeted as end users, it is recommended that the CASL leadership team and staff review the processes used to determine readiness for releases of VERA prior to other Test Stand deployments or a general VERA release.

4. TVA TEST STAND

At the present time, work on the Test Stand at TVA has not commenced. In this section, we provide an overview of the planned application to apply M&S capabilities to evaluate the Lower Plenum Flow Anomaly (LPFA) phenomenon. This section provides a brief overview of the phenomenon and its relevance to PWR operation. It also provides a brief overview of preliminary work performed by TVA and a current status.

TVA has proposed to attempt the simulation of a phenomenon known throughout the industry as Lower Plenum Flow Anomaly (LPFA). LPFA is characterized by periodic shifts in measured local core power postulated to occur as a result of the formation of flow vortices in the reactor vessel downcomer and lower plenum. Other factors, such as loop flow differentials (including geometric differences in loop geometry), reactor coolant pump (RCP) impeller replacement, and RCP start sequence have also been identified as potential contributors to the phenomenon.

At WBN, The magnitude of the difference of measured vs. predicted local power values has been as high as 12% at individual core locations. Operational impacts of the LPFA include reduced departure from nucleate boiling ratio (DNBR) margin and associated operational penalties, increased CRUD susceptibility, and reduced thermal margins (F_q and $F_{\Delta H}$). Several nuclear units have reported observations associated with LPFA and were assessed a DNBR penalty in their safety analysis as a result. Given the industry observations of LPFA and the potentially wide application of simulation results, as well as the application to WBN, TVA is interested in applying the capabilities of CASL's VERA codes towards a simulation of LPFA at WBN.

For their Test Stand application TVA has proposed to use the Hydra-TH CFD methodology / code [11] to evaluate coolant flow in a detailed full core model of the WBN Unit 1 reactor vessel with explicit representations of the vessel inlet region, downcomer, and lower plenum. A full core model (as opposed to a quarter-symmetry model) is required to simulate the phenomenon due to the physical asymmetries in the support structures located in the reactor's lower plenum (called the "lower internals"). The mesh density of these regions will be based upon the relative magnitude and spatial variation of the local flow velocity. Mesh density studies are planned to determine the optimum mesh for these regions.

To reduce computational expense, the reactor core geometry will be represented with a combination of explicit resolution in the baffle and in the upper and lower core plate regions and a homogenized porous medium approximation for fuel assemblies and flow adjacent to the fuel assemblies. The upper internals and vessel outlet region may be explicitly modeled using a coarser mesh, since it is well away from the phenomenon of interest. Fuel assembly components such as spacer grids and guide thimbles will not be explicitly resolved; however, the boundaries of the porous media regions will coincide with the elevations of the grids for possible later studies.

Initially, the simulation will be performed at steady state conditions using measured loop flow rates from a selected Watts Bar operating cycle with single phase flow using the appropriate turbulence model in Hydra-TH (when available). Depending on the results obtained from this initial simulation, additional simulations studying the observed flow condition variations of the loops at Watts Bar may be completed. Follow-on calculations to analyze pump start up effects are proposed, depending upon how conclusive earlier studies are. Finally, the results from the CFD simulations can be used to inform coupled neutronics-channel flow simulations with VERA-CS to illustrate the effects of the identified coolant flow distribution on core power.

It is notable that TVA does not currently own an engineering computing cluster that is capable of running the VERA codes at the required mesh density. Instead, TVA will apply to the Oak Ridge Leadership Computing Facility (OLCF) for an allocation on the Titan supercomputer.

At the present time, TVA is doing preliminary work to develop the necessary solid geometry models and mesh the regions of interest for the sensitivity studies. A simplified geometry has been created and will be used for the mesh sensitivity studies. Additionally, Westinghouse has developed a preliminary Hexpress model of the Watts Bar reactor that could be used to help run Hydra-TH for this Test Stand application. TVA has sent CASL a memo specifying the proposed scope of the simulation and is currently waiting to hear from CASL on whether the requested VERA capabilities are available. The Test Stand will be considered “started” once CASL has evaluated TVA’s proposal and notifies TVA of acceptance.

5. CONCLUSIONS

This report describes experiences obtained from initial Test Stand deployments of VERA to CASL industry partners. At the writing of this report, only the Westinghouse Test Stand has been completed with a comprehensive set of results published. The EPRI Test Stand has been implemented with VERA installed on the EPRI industry class HPC cluster. The TVA Test Stand currently is in the planning phase with actual work not yet started. This current status of each Test Stand is consistent with CASL plans.

In general the Test Stand experiences to date have been positive. However a number of issues did arise during their conduct which provides opportunities for enhancement in terms of both technical capabilities of VERA and in process issues for CASL to address. In assessing the experiences of each of the CASL industry partners that have implemented (or are in the process of implementing) a Test Stand, it is essential to remember that these Test Stands represent *very early deployments* of the VERA technology being developed by CASL. Since these deployments are being made using software that is in the process of undergoing substantial active development, it was anticipated that issues (associated with both technical capabilities of VERA and process issues associated with implementation) would occur. As noted in the previous sections, this indeed occurred. However, given the early stage of development / deployment of VERA, one should view the primary value of the Test Stands as consisting of an opportunity to obtain critical feedback from eventual end users of the technology developed. This feedback can then be evaluated and actions taken to ensure issues that could impact the broad community of external end users are addressed prior to a general deployment to them. The key observations and associated recommendations resulting from the Test Stand deployments are summarized in Table 5-1. A brief synopsis of each of these key observations and recommendations is provided below.

Key Observation	Associated Recommendation
Processes, guidance and CASL support of VERA setup is well structured to support future Test Stands and external VERA deployments. **(Positive Test Stand Outcome)**	N/A
Technical capabilities contained in the VERA Core Simulator produce accurate and robust technical results. **(Positive Test Stand Outcome)**	N/A
Insufficient documentation to support effective end user application of VERA. **(Area for Improvement)**	Provide enhanced focus on end user documentation with particular emphasis on information necessary for end users to be able to successfully develop models and run the associated VERA modules that are necessary to obtain the desired analysis results.
Large amount of computational resources and wall-time required to execute VERA simulations. **(Area for Improvement)**	Future CASL focus on calculation run-time optimization and making a broader range of capabilities available at the lower end of the HPC spectrum (i.e. industry class HPC).
Communications of VERA capabilities and expectations between CASL and end users. **(Area for Improvement)**	CASL review configuration control and release protocols to ensure VERA technical capabilities meet needs / expectations of end users for proposed applications. CASL also review communications protocols to ensure effective and timely communications with end users.

Table 5-1: Summary of Key Test Stand Observations and Recommendations

On the positive side of the Test Stands conducted to date, the set-up of the VERA suite at all of the CASL industry partners can be characterized as being very successful. This experience provides a sound basis to expect that the installations of VERA at other user sites can be accomplished without significant impediments. Based on the Test Stand experiences to date, it also is reasonable to conclude that CASL possesses personnel with sufficient expertise to support such installations and adequately address any issues that may arise.

A second positive outcome was the overall quality of technical results obtained in the Westinghouse Test Stand application to the ZPPT analyses of the **AP1000** PWR advanced first core. The results generated as part of the Westinghouse Test Stand indicate that the VERA core simulator is a robust technical product (at least for capabilities that have been developed and demonstrated to date) that can be applied for high-fidelity core physics simulations of commercial PWRs, including advanced designs like the **AP1000** reactor.

Although these initial Test Stand deployments can, in general, be characterized as successful to date, there are areas where improvements should be made. In the technical area, the level of VERA documentation that is provided to end users needs to be significantly improved, from both engineering functionality and methodology description standpoints. This issue was identified during both the Westinghouse and EPRI Test Stand deployments. Thus the CASL industry partners recommend that significant attention be placed by CASL leadership on this issue prior to a general deployment of VERA to the broader community of stakeholders / end users. A second area where improvements are recommended is in the computational resources and wall-time required by VERA to execute the simulations. Currently (and for the foreseeable future) the vast majority of industry end users have minimal to no access to leadership class HPC platforms (such as Titan at Oak Ridge National Laboratory). Additionally access to industry class HPC capability also is limited for these organizations (typically to platforms in the range of 500 – 1000 compute cores; however it is possible and maybe even likely that this constraint may weaken over the next several years as the cost of industry class HPC platforms decreases). Thus, development of capability for VERA to provide a broader range of capabilities at the lower end of the HPC spectrum would be viewed very positively by the intended user community and is seen as the most critical enhancement that should be pursued by CASL. In addition, from the perspective of the CASL industry partners it is very important that the wall-time must be reduced to allow completion of a simulation within a practical time. As an example, in a core reload analysis a target of approximately 2 days of wall-time to complete a depletion cycle simulation (from core start-up to refueling outage) would be an acceptable upper bound.

A final area for improvement was identified from the EPRI Test Stand experience. As discussed in Section 3, there were different levels of expectations between CASL and the EPRI personnel conducting the Test Stand in the area of the current capabilities associated with the Peregrine code. These differences in expectations were primarily due to communications between the various parties engaged in these activities. As noted in Section 3 it is still early in the EPRI Test Stand deployment and it is fully expected that these issues will be addressed to achieve a satisfactory overall experience. However the “take away” from this experience is that when a general deployment of VERA is made, the capabilities associated with VERA be clearly described (both in terms of what VERA can do but also in terms of what it can’t). Providing a clear description of these capabilities would minimize the risk of an external stakeholder developing unrealistic expectations for the software or misusing it due to some misunderstanding of its capabilities.

REFERENCES

[1] Proposed Test Stand Selection Criteria and EPRI, TVA, and Westinghouse Projects; Consortium for Advanced Simulation of LWRs; September 2012

[2] F. Franceschini, A. Godfrey, et al., Westinghouse VERA Test Stand: Zero Power Physics Test Simulations for the **AP1000**® PWR; L3.AMA.VDT.P8.01 Milestone Report CASL-U-2014-0012-000; March 2014 (Revision 1) (Accessible at the CASL website via the following link http://www.casl.gov/docs/CASL-U-2014-0012-001.pdf)

[3] S. Palmtag, User Manual for the VERA Input Processor; CASL Technical Report: CASL-U-2014-0014-000; November 2013.

[4] T. Evans, F. Franceschini, A. Godfrey, S. Hamilton, W. Joubert, J. Turner; High-Fidelity Neutronic Analysis of the Westinghouse **AP1000**® PWR; CASL Technical Report: CASL-U-2013-0231-000, December 2013.

[5] S. Palmtag, R. Pawloski, R. Montgomery and J. Turner; Initial Demonstration of Peregrine I, VERA-CS; Consortium for Advanced Simulation of LWRs; July 2013

[6] D. Gaston, C. Newman, G. Hansen, and D. Lebrun-Grandi´e; "MOOSE: A parallel computational framework for coupled systems of nonlinear equations"; *Nucl. Eng. Design*; vol. 239; pp. 1768–1778; 2009

[7] R. Montgomery, W. Liu and D. Sunderland; *Peregrine 0.1 Training*; Charlotte, NC, February 6-7, 2014

[8] Fuel Reliability Guidelines: Pellet-Cladding Interaction. EPRI, Palo Alto, CA: 2008. 1015453

[9] S. Hess and R. Montgomery; VERA Requirements Document (VRD) – Revision 1; CASL Techncial Report CASL-U-2013-0146-000; April 2013

[10] Fuel Reliability Program: Falcon Fuel Performance Code, Version 1.2; Palo Alto, CA: Electric Power Research Institute (EPRI); 2012

[11] S. Pannala and A. Stagg; CASL THM: CFD Benchmarks and Test Cases; Consortium for Advanced Simulation of LWRs; March 2012